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A SYSTEMS APPROACH

TO

ROTORCRAFT STABILITY AND

CONTROL RESEARCH

FINAL REPORT

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24 October 1988

U.S. ARMY RESEARCH OFFICE

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Helicopters exhibit undesireable dynamic characteristics due to strong coupling that exists between longitudinal and lateral modes. In addition to being unstable at hover and low forward flight speeds, the helicopter has significantly different dynamic modal characteristing in hover and low speeds as compared to forward flight. For example, in hover, the body translational motion and pitching motion are decoupled from the heaving motion. In forward flight, the pitching motion and the vertical motion are stronglv coupled. These dissimilar characteristics in hover and forward flight make piloting techniques more difficult and increase pilot workload and degrade handling qualities. This research has attempted a syst ms approach to rotorcraft stability and control.

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1. FOREWORD

The overall objective of this research has been to apply a systems approach to rotorcraft stability and control research as illustrated in Figure 1. When this research was first proposed in May 1985, it was becoming more and more evident that this approach was the key to expanding rotary wing aircraft capability through expanded flight envelopes. With respect to basic research areas, two separate sources were utilized to establish the methodology in Figure 1. The first source (Ref. 1) was a document prepared by Mr. David L. Key of the U.S. Army Aeromechanics Laboratory which outlined "Topics for Helicopter Stability and Control Research." The second source (Ref. 2) was the results of an independent assessment of helicopter stability and control for ARO by Dr. Frederick O. Smetana. Both of these source documents have been included in Appendix A of this final report for completeness.

A SYSTEMS APPROACH TO ROTORCRAFT STABILITY AND CONTROL RESEARCH

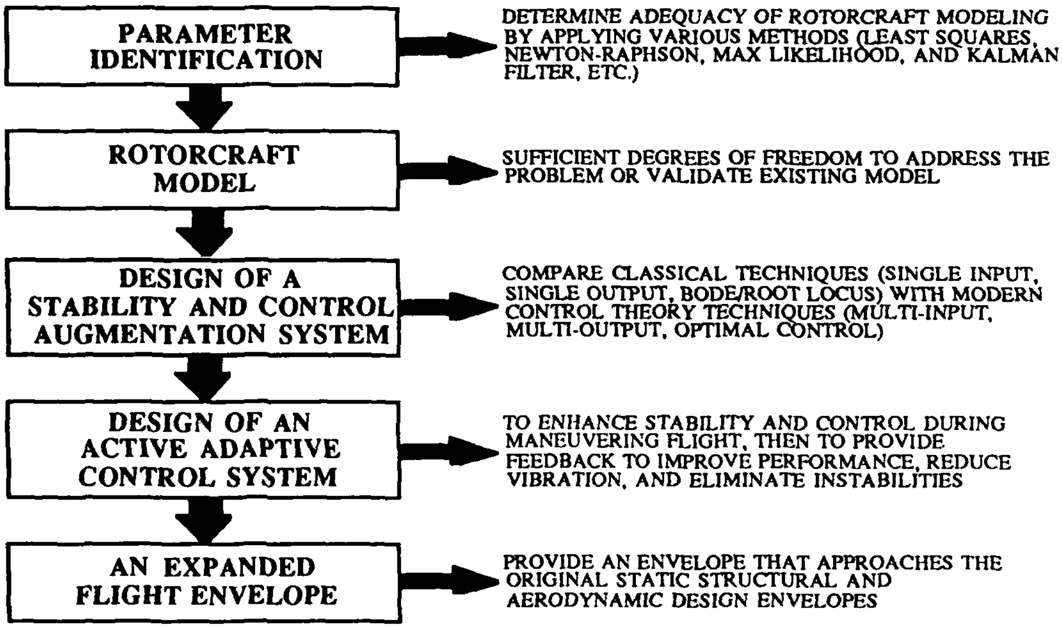


Figure 1

2. TABLE OF CONTENTS

3. List of Appendices, Illustrations and Tables

4. Body of Report

A. Statement of the Problem Studied

Before applying sophisticated modern and active flight control design techniques to rotorcraft, a better understanding of the required mathematical model structure is necessary. Still unanswered questions in rotorcraft stability and control mathematical modeling are the degrees of greedom required in linear models and the proper use of techniques for mathematical model verification and updating from flight test. Therefore, a systems approach to rotorcraft stability and control research is required as illustrated in Figure 1. A systems approach, including parameter identification, rotorcraft modeling, and flight control system design was proposed because these areas address the necessary aspects of stability and control research and are essential to the interaction of the pilot with the vehicle dynamics through the control system. This work was to be accomplished over a three-year period as described in the year-by-year breakout of Statement of Work (SOW) tasks. Unfortunately, this research is being terminated after two years due to ARO funding contraints and the comphrehensive documentation required in the third year will not be accomplished. Considerable progress has been accomplished over the first two years and the research has generated extensive interaction with the U.S. Army, the rotorcraft industry, and NASA. An example of this interaction is provided in Figure 2 which illustrates how this ARO project has generated considerable involvement of the resarchers with other organizations.

Figure 2

The proposed year-by-year breakout of the Statement of Work (SOW) tasks were:

1) Year One:

Task 1: Obtain UH-60A Black Hawk Helicopter Flight Test Data Base, General Helicopter (GEN HEL) Flight Dynamics Simulation Program, NASA AMES Army Copter (ARMCOP) Flight Simulation program, and install on the GIT computer system.

Task 2: Use Black Hawk ARMCOP Model and flight test data to estimate stability and control derivatives in hover and cruise speed. Correlate computed response to actual measured response.

Task 3: Apply parameter identification methods such as least squares, and Modified Newton-Raphson Techniques for the derivative extraction and modify ARMCOP if necessary to meet performance criteria.

2) Year Two:

Task 1: Develop a stablity augmentation system for the Black Hawk Helicopter using both classical and modern control techniques based on the updated math model extracted from flight test data.

Task 2: Repeat Task 1 for the design of a control augmentation system. Investigate a direct method for the selection of the weighting matrices to reduce the trial and error required in the analysis.

Task 3: Generate an adaptive controller from the improved math model to address stability and control effectiveness for varying flight conditions.

3) Year Three:

Task 1: Investigate nonlinear effects, such as actuator dynamics and control authority, and their impact on the flight control system design.

Task 2: Include in the flight control system design the provisions for a higher harmonic controller to provide further envelope expansion.

Task 3: Generate a comprehensive documentation of the methodology used in applying a Systems Approach to Rotorcraft Stability and Control Research and the design of a flight control system.

B. Summary of the Most Important Results

1. Year One:

All three tasks identified were accomplished, although it became clear after extensive investigation that the UH-60A flight test data obtained (Ref. 3) was strongly flawed. The first problem was that no complete documentation was available for the data. The second problem was that the results of preliminary estimation runs indicated physically unrealistic results. The trouble was thought to have been produced by sign convention irregularities and physical units problems. Upon discussion with Sikorsky, the Army, and NASA, these speculations proved to be correct. Similar problems have been found in analyzing flight test data of the AH-64 as part of the AGARD Flight Mechanics Panel (FMP) Working Group (WG) 18 identified in Figure 2. This illustrates the level of immaturity and difficulty in working with rotorcraft flight test data.

Once an understanding of the errors in the UH-60A flight test data was achieved, parameter identification runs were made which indicated a strong variation in the response as a function of noise in the data. In order to address these points, a program was laid out in which a known mathematical model, derived as a reduced order model from the UH-60A ARMCOP model, was used to generate numerical data. This data was then contaminated with a given amount of noise and used in a Recursive Least Squares identification scheme. The model used was a fourth order (longitudinal) one. Results showed that the technique did well in the face of zero noise but poorly for even small amounts of noise.

An Extended Kalman Filter was then implemented to compare to the previous results. This technique showed a strong tendency to diverge and was judged unsuitable for rotorcraft identification purposes at this time. A relatively new technique, the Statistically Linearized Filter, was then utilized. This method worked very well with the zero and small noise cases, but appeared to give incorrect results with moderate noise levels. Finally, the Maximum Likelihood method was investigated to determine its advantages.

The UH-60A ARMCOP model was obtained and used to estimate stability and control derivatives in hover and cruise speed. Correlations of computed response to actual measured response were also obtained. Results of the efforts conducted during the first year have been reported and will be reported in References 4 and 5.

2. Year Two:

Helicopters exhibit undesirable dynamic characteristics due to the strong coupling that exists between longitudinal and lateral modes. In addition to being unstable at hover and low forward flight speeds, the helicopter has significantly different dynamic modal characteristics in hover and low speeds as compared to forward flight. For example, in hover, the body translational motion and pitching motion are decoupled from the heaving motion. Whereas in forward flight, the pitching motion and the vertical motion are strongly coupled. These dissimilar characteristics in hover and forward flight make the piloting technique much more difficult and thus increase the pilot work load resulting in degraded handling qualities. These undesirable characteristics may be substantially reduced by using feedback control for modal decoupling and stability augmentation.

It has been a common practice to use classical techniques such as the root locus technique for the design of helicopter flight control systems. This calls for considerable amount of trial-and-error and experience for a successful design. Because of its time consuming nature, the use of classical techniques, though simple, often result in an

adequate design rather than the best design. Thus, although these techniques have resulted in satisfactory designs in the past, they may not prove adequate for future high performance helicopters. In particular, classical techniques are difficult to use in the design of controllers for systems in which there are several coupled inputs and outputs. However, the use of modern control theory permits the use of multi-variable feedback without much complexity.

There are various methods that are commonly used for multi-variable feedback controller design. A few of the modern control theory techniques that can be used for helicopter flight control system design are

a) Linear Quadratic Regulator Design (LQR)
b) Optimal Output Feedback Design
c) Constrained Optimal Output Feedback Design
d) Model Following
e) Eigenstructure Assignment

All these design procedures except the eigenstructure assignment technique are based on optimal control theory involving the design of the feedback controller based on minimization of a chosen quadratic performance index.

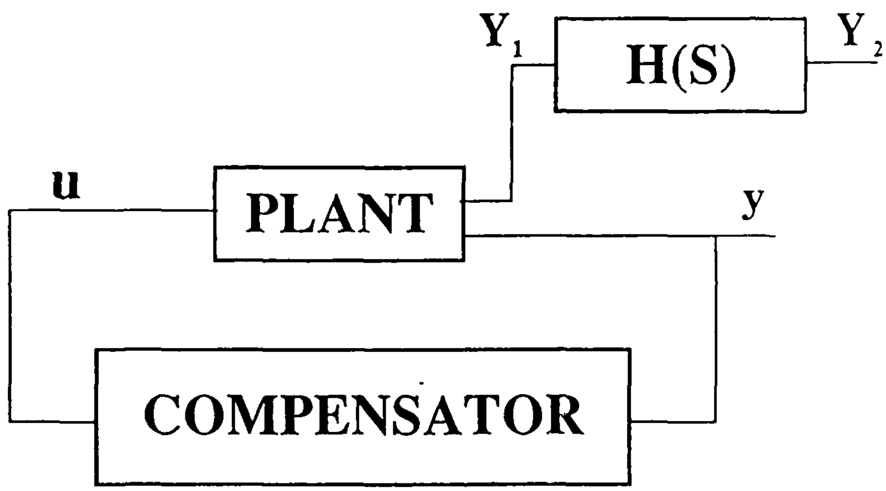
It is well known that Linear Quadratic Regulator (LQR) synthesis methods have guaranteed stability margins in terms of phase and gain margins. Unfortunately, these properties hold only in the case of full state feedback. Observer based compensator design techniques exist to estimate the unavailable plant states, and make the LQR design viable. However, this combination of state estimation and regulation may result in a compensator design with poor stability margins, even though the separate designs are robust. The LQR design for minimum phase plants can be recovered via an asymptotic method called Loop Transfer Recovery (LTR). The LTR method relies on a cheap control formulation with a subset of the compensator dynamics becoming infinitely fast. It is often stated that the order of the compensator can later be reduced by discarding the fast modes; however, it is not clear how this can be accomplished without introducing direct feedthrough of the measured variables. It is generally a good practice to avoid having direct feedthrough of sensor outputs to improve robustness and reduce the effect of sensor noise at high frequency. Aside from robustness issues, the order of the resulting compensator when designed for large order systems may prove unwarranted.

Optimal output feedback design of fixed-order compensators introduced in the early seventies has received limited attention due to numerous difficulties associated with the design approach. Part of the difficulty lies in the fact that the compensator representation initially proposed was overparameterized. That is, the compensator formulation lacked a predefined structure, which invariably results in convergence problems when attempting to numerically optimize the design. Since that time, several people have adopted canonical structure which results in a minimal parameterization. In spite of the simplification achieved through canonical structure of the compensator, the optimal output feedback design approach lacks the ability to characterize the stability margin properties.

As part of the second year effort, the optimal output feedback with fixed order compensator design approach has been investigated for improvements. On the outset, the optimal output feedback design approach is well suited for helicopter flight control system design as compared to other multi-variable feedback control design techniques. This is due to the fact that the output feedback controller is easy to realize in terms of required hardware. Because of very high vibratory environment, only certain states of the helicopter can be measured accurately and inexpensively, e.g., body attitudes, body angular rates. Thus output feedback design approach offers a direct advantage in terms of its ability to

make use of available measurements for feedback. The modifications made to the output feedback design approach as part of this study are presented in the following paragraphs.

One of the major objections to optimal output feedback design are that there are no guarantees on stability margins, and there are few guidelines for penalizing the plant states and compensator states to improve either performance or robustness. In order to address these issues, the use of frequency shaped cost functionals in an optimal output feedback setting was considered based on the work by Mehra (Ref. 6) wherein the concept of frequency shaped cost functionals was first introduced in a full-state feedback design. This method is a result of embedding classical design concepts within LQ optimal design and it is well suited for damping of widely separated structural modes and disturbance rejection over a narrow frequency range. However, in the design approach followed in Ref. 6, the frequency shaper (filter) is part of the feedback controller and it has to be physically realized for actual implementation of the design. Whereas in the present work, the output of the frequency shaper (filter tuned to a particular frequency) is used only in the performance index and hence, the filter need not be realized as part of the compensator (see.Figure 3).



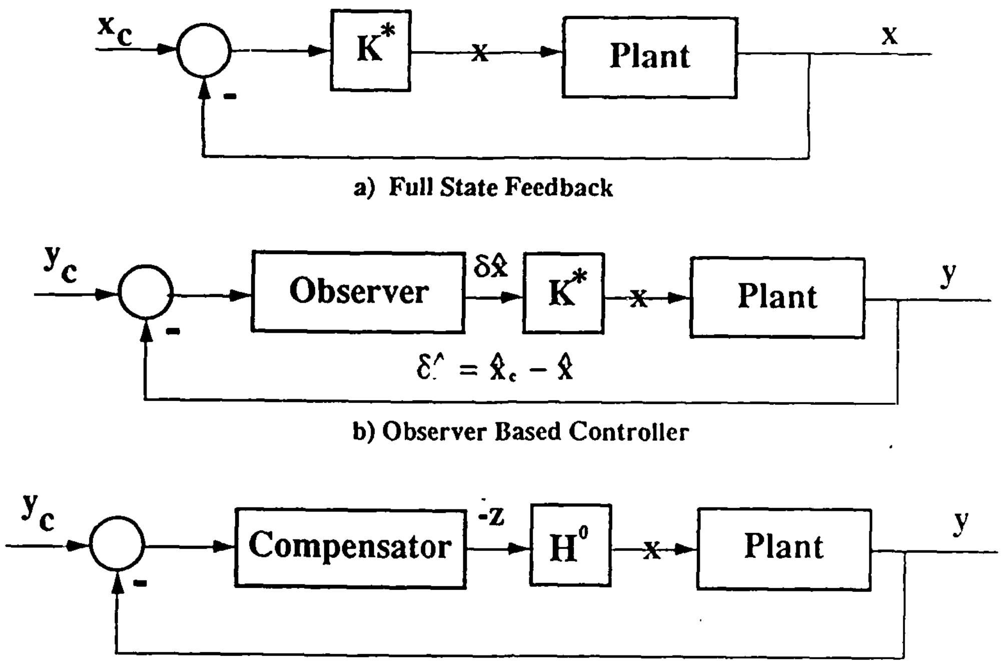
Performance Index:

$$J = E_{xo}\left\{\int [y_2{}^t Q y_2 + u_c{}^t R u_c] dt\right\}$$

Figure 3

This method was successfully implemented on two example design problems. The first example deals with helicopter active vibration control (Ref. 7) and the second example deals with improvement of damping of the structural modes (Ref. 8). Though this method is well suited for active control of helicopter vibration, the procedure becomes complicated when this method is used for helicopter flight control system design.

Another way of achieving robustness is the approximate loop transfer recover procedure developed as part of the ARO Center of Excellence for Rotary Wing Aircraft Technology (CERWAT) contract. The full-state and output feedback structures are illustrated in the Figure 4.



a) Full State Feedback

b) Observer Based Controller

c) Fixed Order Controller

Figure 4.

The objective in observer-based controller design is to estimate the plant states, and to use the estimated states in place of the actual states. This results in a higher order system where closed-loop eigenvalues and eigenvectors of the full-state design are preserved, and the compensator merely adds its own dynamics to the response. When the compensator is designed based on loop transfer recovery, it is also possible to recover the gain and phase margin properties of the full-state design. This amounts to suitably choosing the weighting matrices in a dual LQR formulation for the observer design. Both full-state and observer design problems are decoupled. In fixed-order compensator design using output feedback, the notion of state estimation is not present. However, it should be recognized that, so long as the loop transfer properties of a full-state design can be recovered to a sufficient degree of accuracy, then the closed loop eigenvalues should contain a set of eigenvalues and eigenvectors that approximate those of the full-state design. Most importantly, the multivariable gain and phase margin properties should also be approximated, With this in mind, consider the loops broken at the points marked x in Figure 4. The loop transfer properties of both loops are nearly equal when the time response of the signals at the the return of the loop are approximately equal for a set of identically chosen input signals, with zero initial conditions on all states in the two feedback systems. This recovery procedure can be viewed as a rationale for properly selecting the plant and compensator state weighting, and the initial condition distribution matrix. This design procedure was successfully used in the design of a tight attitude control system for the Sikorsky S-61 helicopter in hover flight condition (Ref. 9). Also, the same design approach is used for the Black Hawk helicopter flight control system design in satisfying the updated helicopter handling qualities specifications and the results will be presented at the upcoming International Conference on Helicopter Handling Qualities (Ref. 10).

Also, as part of this study, the approximate loop transfer recovery procedure described in the previous paragraph is implemented in a two-time scale controller design and the results are submitted for publication to the ASME Journal of Dynamic Systems (Ref. 11). The two-time scale controller design is particularly well suited for active control of rotor dynamic characteristics. In this method, the overall design is simplified in terms of design of a slow controller for slow dynamics and a fast controller for the fast dynamics. The procedure of designing individual controllers becomes decoupled when the fast subsytem design is carried out with certain constraints placed on it and the composite controller is obtained by adding the fast controller and the slow controller.

Based on the results obtained as part of this study, it is concluded that optimal output feedback approach offers a great potential in the design of very tight controllers for envelope expansion and hence, this design procedure is very useful in designing flight control systems for future high performance rotorcraft.

C. List of All Publications Produced under this Research Contract

1) Fitzsimons, P.M., Teare, D., Prasad, J.V.R., Schrage, D.P. and Tongue, B.H., "Some Basic Issues in Helicopter System Identification," presented at the <u>2nd International Conference on Basic Rotorcraft Research</u>, University of Maryland, February 16-18, 1988.

2) The following presentations were made at <u>The Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems</u>, Sponsored by the ARO and Florida Atlantic University in Boca Raton, Florida, on November 18-20, 1987:

   a) Calise, A.J. and Jonnalagadda, V.R.P., "Compensator Based Controller Design for Helicopters," Georgia Institute of Technology.

   b) Schrage, D.P., Oakes, G., and Jonnalagadda, V.R.P., "Development of an Individual Blade Control Computer Analysis," Georgia Institute of Technology.

   c) Schrage, D.P., Jonnalagadda, V.R.P., and Wasikowski, M.E., "Active Vibration Control Using Reduced Order Models," Georgia Institute of Technology.

3) Calise, A.J. and Prasad, J.V.R., "An Approximate Loop Transfer Recovery Method for Designing Fixed-Order Compensators," Presented at the <u>AIAA Guidance, Navigation and Control Conference</u>, August 1988.

4) Schrage, D.P., Tongue, B.H., Prasad, J.V.R., Fitzsimons, P.M., and Teare, D., "Time Domain Parameter Identification Techniques Applied to the UH-60A Black Hawk Helicopter Flight Test Data, " Paper to be included in special edition of <u>Vertica</u> Magazine on Helicopter System Identification, December 1988. (Abstract in Appendix B)

5) Prasad, J.V.R. and Schrage, D.P., "Comparison of Helicopter Flight Control System Design Techniques," to be presented at the International Conference on Helicopter Handling Qualities and Control, London, England, November 16, 1988. (Abstract in Appendix B)

6) Calise, A.J., and Prasad, J.V.R., "Fixed-order Compensator Design Based on Frequency Shaped Cost Functionals," to appear in the Journal of Guidance and Control.

7) Siciliano, B., Calise, A.J. and Prasad, J.V.R., "Two-Time Scale Stabilization of a Flexible ???? with Output Feedback," submittted for publication to the ASME Journal of Dynamic Systems, Measurement and Control, 1988.

D. List of All Participating Scientific Personnel

Name	Organization	Advanced Degree Earned
D. P. Schrage	School of Aerospace Engineering	N/A
J.V. R. Prasad	School of Aerospace Engineering	N/A
B.H. Tongue	School of Mechanical Engineering	N/A
P.M. Fitzsimmons	School of Mechanical Engineering	N/A
D. Te?re	School of Mechanical Engineering	M.S., March 1988

5. References

The following are publications referenced in the body of this report:

1. Key, D.L., Memorandum for Record, 26 November 1984, Subject: Topics for Helicopter Stability and Control Research, Aeromechanics Laboratory, U.S. Army Research and Technology Laboratories - AVSCOM, Ames Research Center, Moffett Field, CA 94035

2. Smetana, F.O., Letter, received 24 September 1984, Subject: Helicopter Stability and Control Research Needs, Engineering Sciences Division, U.S. Army Research Office

3. Abbott, W.Y., et al., USAAEFA Project No. 79-24, Validation Flight Test of UH-60A for Rotorcraft Systems Integration Simulator (RSIS), September 1982

4. Fitzsimons, P.M., Teare, D., Prasad, J.V.R., Schrage, D.P. and Tongue, B.H., "Some Basic Issues in Helicopter System Identification," presented at the 2nd International Conference on Basic Rotorcraft Research, University of Maryland, February 16-18, 1988.

5. Schrage, D.P., Tongue, B.H., Prasad, J.V.R., Fitzsimons, P.M., and Teare, D., "Time Domain Parameter Identification Techniques Applied to the UH-60A Black Hawk Helicopter Flight Test Data, " Paper to be included in special edition of Vertica Magazine on Helicopter System Identification, December 1988.

6. Gupta, N.K., "Frequency-Shaped Cost Functionals: Extension of Linear Quadratic-Gaussian Methods," Journal of Guidance and Control, Vol. 3, Nov.-Dec., 1980, pp. 529-535.

7. Schrage, D.P., Jonnalagadda, V.R.P., and Wasikowski, M.E., "Active Vibration Control Using Reduced Order Models," presented at The Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Sponsored by the ARO and Florida Atlantic University in Boca Raton, Florida, on November 18-20, 1987.

8. Calise, A.J., and Prasad, J.V.R., "Fixed-order Compensator Design Based on Frequency Shaped Cost Functionals," to appear in the Journal of Guidance and Control.

9. Calise, A.J. and Prasad, J.V.R., "An Approximate Loop Transfer Recovery Method for Designing Fixed-Order Compensators," Presented at the AIAA Guidance, Navigation and Control Conference, August 1988.

10. Prasad, J.V.R. and Schrage, D.P., "Comparison of Helicopter Flight Control System Design Techniques," to be presented at the International Conference on Helicopter Handling Qualities and Control, London, England, November 16, 1988. (Abstract in Appendix B)

11. Siciliano, B., Calise, A.J. and Prasad, J.V.R., "Two-Time Scale Stabilization of a Flexible Arm with Output Feedback," submittted for publication to the ASME Journal of Dynamic Systems, Measurement and Control, 1988.

6. Appendicies

Appendix A. Source Documentation on Rotorcraft Documentation of Rotorcraft Stability and Control Research Needs

Appendix B. Abstracts for Forthcoming Publications

DEPARTMENT OF THE ARMY
AEROMECHANICS LABORATORY
US ARMY RESEARCH & TECHNOLOGY LABORATORIES-AVSCOM
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA 94035

SAVDL-AL-C

26 November 1984

MEMORANDUM FOR RECORD

SUBJECT: Topics for Helicopter Stability and Control Research

1. The ongoing efforts at the Aeromechanics Laboratory in stability, control, handling qualities and pilot aircraft interface are generally at the 6.2 Exploratory Development level and involve use of sophisticated experimental facilities. However, there are many topics related to this program that could be considered 6.1 Basic Research that are essentially analytical and require primarily computational support; such topics could usefully be addressed by universities and small analytical research companies and perhaps supported through the U.S. Army Research Office. The following is a brief listing of some such topics:

a. Rotorcraft Modeling

(1) The degrees of freedom required in linear models.

(2) Techniques for math model verification and updating from flight test.

b. Modern Control Theory Applications

(1) Use of optimal and modal control law implementation approaches, i.e., both time and frequency domain approaches. We particularly need to assess methods that can minimize feedback gain levels.

c. Digital Flight Control System Effects

(1) Study the effects of digital computation delays and interaction with rotor and structural dynamics on the performance of high-gain digital flight control systems.

(2) Methods for direct digital design--rather than converting from continuous system designs.

e. Active Control Applications

(1) Techniques for applying active horizontal stabilizer, higher harmonic control, integration of the propulsion and flight control system, and relaxed static stability configurations.

f. Real-Time Expert Systems Development

(1) Applications of expert systems to flight path management, could include functions such as automation of NOE navigation, terrain avoidance, terrain following, threat avoidance, failure sensing and recovery.

g. Simulation Technology

(1) Quantification of visual and motion cue effects.

(2) Math modeling techniques to minimize computation times.

(3) Air combat simulation requirements.

h. Effects of Outside Visual Cue Quality

(1) Relate the characteristics of both outside visual scene and sensor/display quality to human perceptual capabilities and flight path control limitations.

i. Turbulence Model

(1) There is a need for development of a low-altitude turbulence model for incorporation into the updated handling qualities Spec 8501.

j. Maneuvering Envelope Limiting and Cueing

(1) Need to understand fundamental envelope maneuver limitations and how these can be cued to the pilot to inhibit him from violating these limits but allowing him to exceed them in emergency situations.

k. Energy Management Techniques

(1) Apply optimization methods to air combat, autorotation, and engine-out operations.

SAVDL-AL-C 26 November 1984
SUBJECT: Topics for Helicopter Stability and Control Research

1. Interactional Aerodynamics

(1) Better techniques for developing stability and control predictions especially applied to empennage design.

2. If further explanation or discussion of potential responses to these topics is required, please contact the undersigned (415) 694-5839 or Ed Aiken (415) 694-5362.

David L. Key

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HELICOPTER STABILITY AND CONTROL RESEARCH NEEDS

by
Frederick O. Smetana
Engineering Sciences Division
U.S. Army Research Office

I. Introduction

The Army Research Office currently supports no research directed specifically toward improved methods for controlling the response of a helicopter to pilot commands or gust excitations. Given this knowledge, members of the Army research community have expressed concern that new helicopter designs will place such severe demands on the pilot for flight path management that he will be unable to carry out his mission successfully. These researchers are further concerned that the technology base for alleviating these demands on the pilot does not now appear to exist within the Army laboratories or its helicopter contractors. The writer was asked to investigate the situation and to recommend a suitable research program in the event that these concerns were justified.

Visits were made to the Aeromechanics Laboratory and to Bell, Vertol, and Sikorsky to attempt to obtain a feel for the level of technical sophistication available or in use at these installations and for the management philosophy regarding the employment of sophisticated technology. The Aeromechanics Laboratory has a major program underway to procure an integrated collection of computer programs which calculate such things as vehicle aerodynamics, structural dynamics, flight dynamics, and performance given the vehicle configuration, power plant, and structural layout. The design for the executive program of the collection has been fixed and the desired capabilities of most of the modules in the collection seem to have been established. The writer received the impression that these modules would be provided with numerous switches to enable various options. The sophisticated user would be able to vary the complexity of the calculations considerably to permit a variety of accuracy/cost needs to be satisified. It will, however, require someone with a good feeling for what is needed in a particular circumstance to take advantage of these features.

The basic technological sophistication of the individual modules seems to be restricted by two considerations: (1) a recognition that each module is part of a larger whole and must run in a reasonable period of time, and (2) the methods programmed must be well-accepted. This effectively locks them to the present state of helicopter aerodynamic computation and control system technology. However, because of the modular design of the overall program, individual sections can be replaced as more effective methods become available.

Perhaps because the helicopter is a more complex flying machine than are fixed-wing craft, engineers in the helicopter industry have tended to use empirical data correlations and cut-and-try approaches more than have engineers in the fixed-wing industry. As a result, they appear, on the basis of the writers' interviews, to be less well-informed on the subtleties of new analysis methods and less able to take advantage of them than are their brothers in the fixed-wing industry. The cash flow generated by current low

production rates in the helicopter industry may also have something to do with this situation though it appears to be a result of a long-term mindset.

The writer did not attempt to compare the requirements of an LHX mission with currently available technology to determine the extent to which concerns voiced by Army laboratory personnel are valid. He observes only that the following situation exists:

(1) The helicopter industry is generally behind the fixed-wing industry in the employment of sophisticated aerodynamics and flight control analysis tools.

(2) Mission success is inversely related to the severity and complexity of pilot workload.

(3) Current helicopters are more demanding and less forgiving of errors than current fixed-wing craft.

Given this situation, a research program such as that described below is justified. Sections II and III provide some additional detail on the relationship between five suggested research tasks outlined in Section IV and current practice in aerodynamics and control system design.

II. Aerodynamics

The determination of the motion of a helicopter as a result of a control input or excitation by a gust requires a knowledge of the aerodynamic forces acting on the craft during its response. For fixed-wing aircraft undergoing relatively small displacements from equilibrium, these forces are usually represented by the first terms of Taylor series expansions in the linear and angular velocity components of the vehicle motion, accelerations, and aerodynamic and/or inertial angles, e.g.,

$$L = L_0 + \frac{\partial L}{\partial U}(U_1 - U_0) + \frac{\partial L}{\partial \upsilon}(\upsilon_1 - \upsilon_0) + \frac{\partial L}{\partial W}(w_1 - w_0) + \frac{\partial L}{\partial q}(q_1 - q_0) + \cdots$$

The partial derivatives in such expressions are taken to be constants and must be evaluated a priori from wind tunnel or flight test data or by suitable theoretical computation. The more accurately these values are known, the more accurately the vehicle motion can be determined and the more easily the need for installing or retaining non-linear terms in the equations of motion can be ascertained.

Conversations with engineers in the helicopter manufacturing industry have revealed that their knowledge of the values of these "stability derivatives" for specific configurations is relatively crude or even non-existent, particularly when the vehicle is in vertical or sidewise motion. There apparently has not yet been a concentrated national effort (as there was for fixed-wing vehicles) to develop a comprehensive and generally-accepted set of evaluation procedures for these derivative values. It would appear that development of at least some of these procedures must await the results of tests now being conducted or planned for the near future and the completion of large computer codes which are capable of accurately modeling rotor-fuselage

interactions, rotor-tail rotor interactions, and fuselage wakes in vertical and sidewise motion. While the knowledge to prepare such codes is thought to exist, they apparently have not as yet been contracted for.

III. Flight Dynamics and Control System Design

Oral queries of engineers in the helicopter manufacturing industry have led the writer to the conclusion that current flight path management and mission management systems do not take full advantage of modern digital control design methodology and hardware implementation or of recent research results on means of reducing the pilot workload and enhancing his performance. It is the writer's impression that current design methodology proceeds more or less along the following path:

1. Review design requirements; formulate an optimal control problem which models the proposed system in a fairly crude fashion; solve this problem to determine control laws which offer the better opportunities to produce the desired result.

2. Model the vehicle plus the proposed control laws in a linear fashion; using classical linear control theory, perform design analyses to estimate the system gains required.

3. Construct actual system hardware; connect to simulator of vehicle; adjust system gains or modify control laws to give desired result.

4. Fine tune control system gains or modify control laws as a result of flight tests.

There is considerable cut-and-try to this process that probably achieves suboptimal results in a longer-than-necessary time span.

IV. Research Needs

(1) Determination of Aerodynamic Stability Derivative Values. A two-phase research effort is envisioned to provide more accurate aerodynamic data for use in flight path determinations: (a) Comprehensive, rigorous analysis of the flow field around specific, complete helicopter configurations in (i) hover, (ii) forward flight--at both low and high advance ratios, (iii) vertical flight, (iv) sidewise flight, and (v) rearward flight leading to determinations of the lift, drag, side force, pitching moment, rolling moment, and yawing moment as functions of angle of attack, angle of sideslip, pitch angle, yaw angle, roll angle, flight path velocity, rotor RPM, cyclic pitch, collective pitch, tail rotor RPM, and their first and possibly second derivatives with respect to time. (b) Correlation of the foregoing theoretical results with wind tunnel and flight results to develop simplified--possibly semi-empirical--methods to predict the values of all significant derivatives, these methods to be suitable for preliminary design and some detail design in the manner of the DATCOM for fixed wing aircraft.

(2) Develop the Control Laws, Control Means, and Sensor Requirements for Decoupling the Three Components of Linear Velocity as well as the Three Components of Vehicle Attitude. Much of the pilot workload in flight path management is a result of the need to coordinate the various controls avail-

able to him. Decoupling removes the need for such coordination and frees the pilot to undertake mission management functions. An integral part of the control law and associated display development should be a consideration of the requirements and abilities of the pilot. A second phase of the investigation should be a handling qualities evaluation (and refinement if necessary) of the resulting control laws and displays in a simulator.

(3) Determine the Effects of an Elastic Vehicle Structure on the Performance of a High-Gain Flight Path Management System and Methods to Suppress Undesirable Coupling. A simulator study of which coupling effects are undesirable also seems indicated.

(4) Determine the Most Suitable Applications for Digital Control Technology to Helicopters. Considerations in this study should include availability of suitable hardware or its potential for development and any improvements in handling qualities which can be anticipated from the implementation of digital control technology. Suitable should be interpreted in terms of size, weight, cost, reliability, and maintainability.

(5) Determine a Proper Role for "Modern Control" Analysis in Helicopter Control Systems Design. The modern control approach seeks to maximize or minimize some performance function by varying the gains in the vehicle control laws. Classical approaches consider the various control loops separately and seek only to vary the gains sufficiently to satisfy preset specifications. By choosing weights in the performance function or adding additional terms to it, considerations of size, cost, and accuracy can be included in the global maximization or minimization. Construction of a suitable performance criterion, however, is perhaps still an art. A study of how one should proceed to do this in a systematic way would be very much in order.

The foregoing research needs can be investigated in parallel efforts. Task #1 is by far the most difficult, requiring perhaps three times the effort of one of the others. Tasks 2 and 3 should be conducted in conjunction with an existing simulator to save time and money.

It is probable that satisfactory results can be obtained from tasks 4 and 5 over a 3-year period at a level of about $115,000/year each. Tasks 2 and 3 can be anticipated to require the same resources exclusive of the costs associated with the operation of the simulator.

Task 1, which should be given the highest priority, can be expected to require funding at the level of $180,000/year for five to six years.

Appendix B
Abstracts of Papers to be Presented

Time Domain Parameter IdentificationTechniques Applied to the UH-60A Black Hawk Helicopter

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Abstract

This study is directed towards the modeling and system identification of rotorcraft. The assumed models are Linear Time Invariant (LTI) perturbation models about the helicopters "trimmed" flight condition. Parameter identification is applied to the assumed models using flight test data from Sikorsky's UH-60A Black Hawk Helicopter. The parameter identification techniques used are Least-Squares and Maximum-Likelihood. The "trimmed" flight conditions are forward flight at 100 knots and hover.

Comparison of Helicopter Flight Control System Design Techniques

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Abstract

The revised handling quality specifications (ADS 33) will have an impact on the techniques used for helicopter flgiht control system design. Traditionally, classical control methods have been used in the determination of the control law and a matrix of control gains involving a trial and errror application of analysis procedures until the presified performance criteria are satisfies. The prodedures are larely a graphical portrayal of Bode, Nyquist, and root locus techniques for the analysis of open loop and closed loop systems. In modern control theory, synthesis of a flight control system proceeds more directly than in classical control theory. It allows the designer more freedom to work directly with the system eigenvalues and eigenvectors. Of course, an iterative procedure must still be performed to meet specified time domain specifications. The advantages of optimal control theory are substantial since a stable, multiple-input/multiple-output flight control system can be designed directly in an optimal sense with relatively small manpower investigations. This means a particular component of the response can be treated without aggravating other

responses such as those associated with handling qualities and vibration. One of the disadvantages of optimal control methods is that it is difficult, in a stable numerical sense, to enforce state, control, and measurement constraints except by a trial and error method involving state and control weighting matrices Q and R. Also, it is not generally possible to enforce relative stability, in terms of frequency domain stability margins, even though the system is guaranteed stable in an absolute sense. An additional disadvantage for rotorcraft applications is that all the states need in the control law development are not measureable, resulting in added complexity in the control system. Though the optimal output feedback with compensator design technique reduces this added complexity somewhat, the design procedure involves the solution of a set of nonlinear equations for control law development, resulting in nonuniqueness of the solution. Thus it can be seen that there a advantages an disadvantages with both classical and modern control design methods and that a hybrid method if probably the acceptable alternative. In order to gain insight into how the two types of methods might be combined in flight control system design, this paper deals with the design of a flight control system for the UH-60 Black Hawk helicopter using both classical and modern control theory techniques. These designs are aimed at satisfying certain criteria taken from the revised handling quality specifications. The resulting designs are compared in terms of hardware realization and complexity in the design process and recommendations are made for a unified design approach.